

LIGHT-PRESSURE EXPERIMENTS BY P. N. LEBEDEV AND MODERN PROBLEMS OF OPTOMECHANICS AND QUANTUM OPTICS

Valentina M. Berezanskaya, Igor Ya. Doskoch, and Margarita A. Man'ko*

*Lebedev Physical Institute, Russian Academy of Sciences
Leninskii Prospect 53, Moscow 119991, Russia*

*Corresponding author e-mail: mmanko@sci.lebedev.ru

Abstract

In connection with the 150th Anniversary of P. N. Lebedev, we present historical aspects of his scientific and organizing activity and recall his famous experimental observations and proof of the existence of light pressure along with other results that essentially influenced the development of physics in Russia and in the whole world as well. We discuss the relationship of these studies of electromagnetic waves and other kinds of vibrational phenomena investigated by P. N. Lebedev to modern studies of the interaction of photons with mirrors, gravitational waves, acoustic waves, nonstationary (dynamical) Casimir effect of photon creation in resonators with vibrating boundaries, and vibrations of voltage and current in superconducting circuits realizing the states of qubits and qudits. We discuss the possibility of existence of the nonstationary Casimir effect for gravitational waves and sound in liquid helium.

Keywords: history of physics, P. N. Lebedev, light pressure, nonstationary Casimir effect, superconducting circuit, gravitational waves, sound in helium.

1 Introduction

From the very beginning of studying the properties of light and the applications of optical instruments, e.g., in astronomy, the nature of light and the understanding of the essence of optical phenomena has attracted the attention of researchers. Today, the results of such researches reflecting the efforts of investigations of many centuries in different countries can be formulated using two different pictures. One picture corresponds to the so-called corpuscular theory of light where the light propagation is considered as a collection of moving particles. The other picture corresponds to the propagation of waves either in the empty space or in the media, and the waves demonstrate all phenomena known for the waves such as diffraction and interference confirmed by many optical experiments.

On the other hand, an important ingredient in understanding the properties of light is to explain how the light interacts with matter. Since the light can be reflected by a mirror, this reflection is associated with the light action on the material of the mirror. From the corpuscular picture of the light propagation, it is quite clear that the particles kicking the mirrors and being reflected by the mirror must press on this mirror. Nevertheless, even such a clear picture in physics should be proved experimentally. The name of Prof. P. N. Lebedev, whose the 150 Years Jubilee we are celebrating, is connected with this fundamental problem.

In this paper, we review the Lebedev experiment described in [1]. The other goal of this paper is to discuss some modern problems of quantum optics and optomechanics connected with recent new experiments such as the observation of photons created from the vacuum in resonators with moving

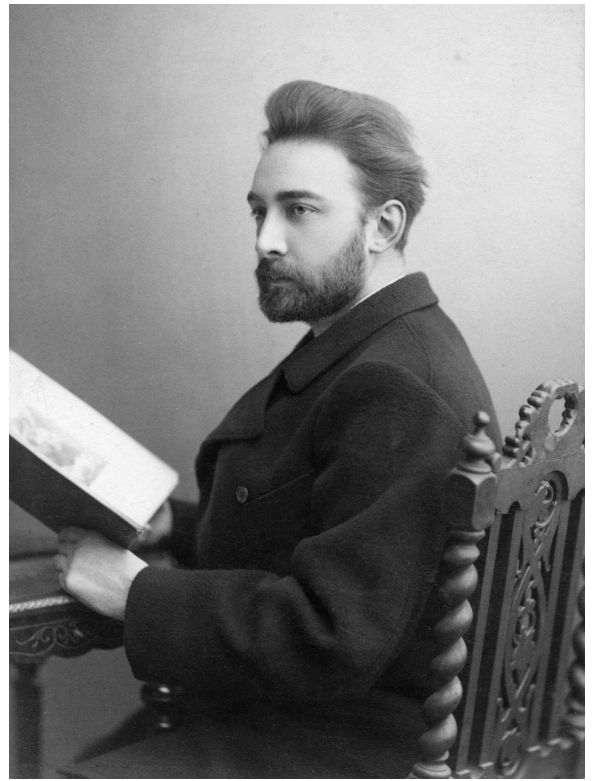
boundaries based on Josephson-junction superconducting devices [2] and the observation of gravitational waves [3]. Also we discuss the other wave phenomena studied by P. N. Lebedev such as the experiments with waves on the water surface. The acoustic waves related to the sound propagation in media were the subject of his research as well. The organization of the work of this group of physicists, who were pupils of P. N. Lebedev, and the creation of the laboratory which grew later to become the Physical Institute, will also be discussed in this paper. We recall P. N. Lebedev's project of gathering the scientists and creating the scientific laboratory, which grew fast and later on was transformed to the Lebedev Physical Institute.

2 Light Pressure

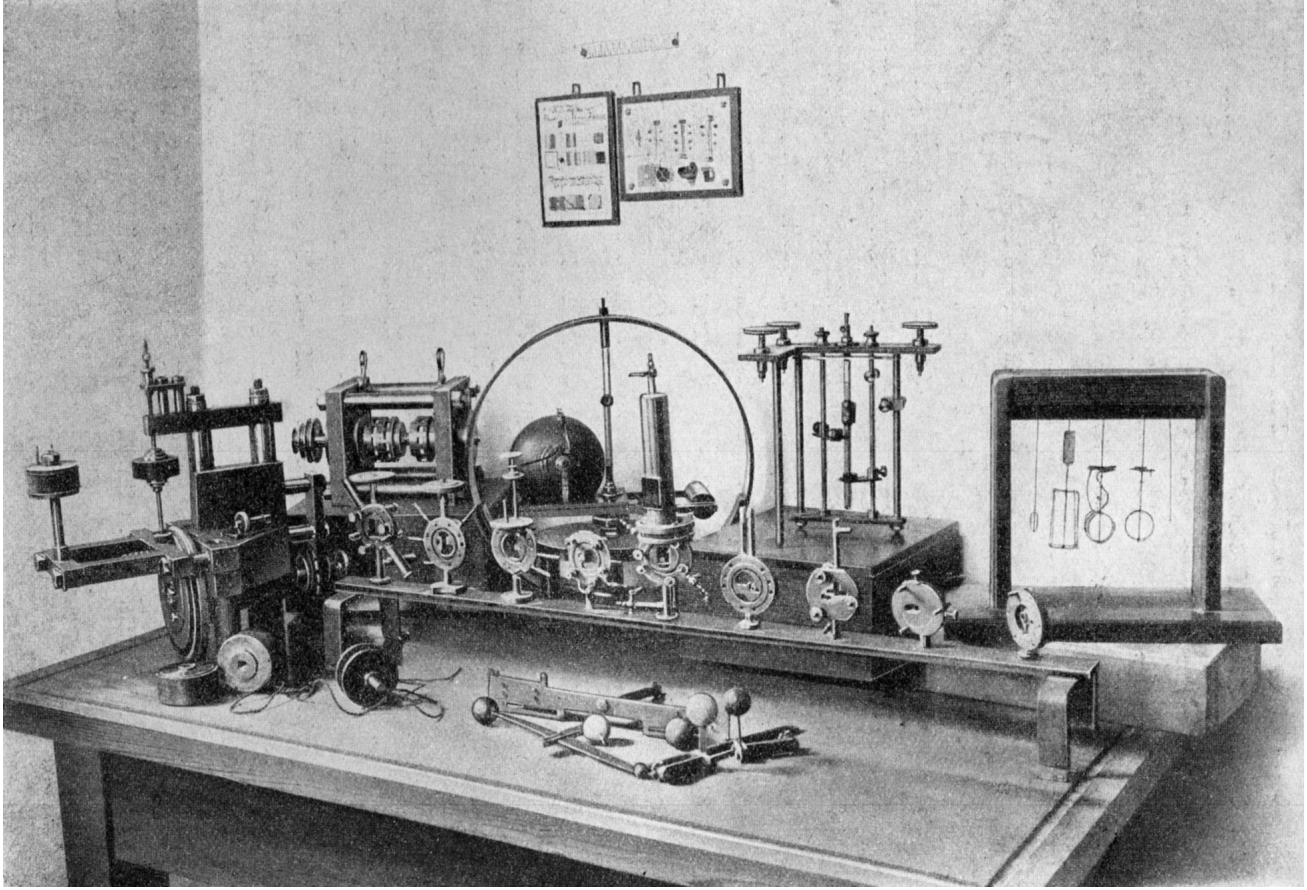
The central result of P. N. Lebedev was experimental observation of the light pressure published in *Annalen der Physik* in 1901 [1]. The existence of the light pressure directly follows from the Maxwell equations, which have solutions describing the electromagnetic waves. These waves are associated with vibrations of the electric and magnetic fields propagating in vacuum with the light velocity $c = 299,792,458$ m/s (or $c \approx 300,000$ km/s). The Maxwell equations connect vibrations of the magnetic and electric fields in an explicit form, and these vibrations carry the energy. The properties of light were discussed in our paper [4] dedicated to the International Year of Light and Light-based Technologies announced by the UN General Assembly for 2015, where historical aspects of the study of light performed during several centuries along with modern results in the area of both fundamental research of quantum phenomena in photon systems and applications of laser technologies were presented.

Electromagnetic waves interact with matter. This interaction can be explained as follows. We assume that one has a pendulum. The pendulum is a massive body that can vibrate with a specific time period or with a specific frequency ω . If one exerts on the pendulum a force that is just in resonance with the pendulum vibrations, the pendulum starts to oscillate with increasing amplitude. This means that the pendulum takes the energy from the source which acts on the pendulum. Having this picture in mind, P. N. Lebedev considered small objects including molecules as analogs of such macroscopic pendulums. The electromagnetic waves with frequencies corresponding to light of different colors provide the energy of magnetic and electric field vibrations to the small pieces of the macroscopic object. There is an analogy of the same phenomenon if one considers the water waves on the surface of a lake. If there is a boat on the lake, the waves on the lake reach the boat, and the boat feels the action of the force associated with the waves. The boat starts to move.

P. N. Lebedev and other physicists of this period of time (80th–90th years of the XIX Century) have



P. N. Lebedev



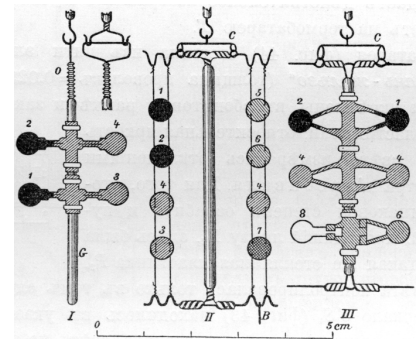
P. N. Lebedev experimental equipment.

a clear understanding of the physical phenomena of the prequantum era. All the vibrations, such as the acoustic vibrations in the air, hydrodynamic vibrations, and electromagnetic vibrations, have common properties. The difference is what vibrates when, e.g., acoustic waves of the sound propagate in media or when electromagnetic waves propagate in the vacuum or in media.

In the acoustic waves, the pressure and density of the air vibrate, and these vibrations are connected due to the wave equation of the sound. In the electromagnetic waves, the electric and magnetic fields vibrate, and the vibrations are also described by the wave equation, which directly follows from the Maxwell equations.

It is worth noting that, as is known, the Einstein equations of the general relativity theory also provide the wave equation for small perturbations of the gravitational field. The Einstein equations are different from the Maxwell equations. Nevertheless, they have solutions corresponding to the gravitational waves. Recently [3] gravitational waves acting on mirrors of LIGO (Light Interferometer Gravitational-Wave Observatory) detector were observed. This result is an experimental observation of the action of gravitational radiation on a macroscopic object such as a mirror.

This observation is a complete analog of the experiment performed by P. N. Lebedev, where the



Different wing models for Lebedev's experiments.

action of the electromagnetic radiation on a macroscopic object was observed in very sophisticated but convincing experiment. In the discussed phenomena, the universal properties of the vibrations and waves of arbitrary nature are demonstrated. In fact, the sound, light, surface waves on water, and the gravitational field vibrations seem to be (and they are) absolutely different physical phenomena. But all of them have common features and common behavior. The vibrations and waves carry energy, and the waves act on the matter and macroscopic bodies, and this action is analogous to the light pressure observed and measured by P. N. Lebedev.

3 Quantum Era

P. N. Lebedev passed away in 1912, being only 46 years old. His scientific activity was dedicated to classical physics phenomena since the quantum revolution in understanding the physical nature of behavior of photons, electrons, and atoms was at the beginning of the Twentieth Century in a very initial but fast developing stage. The result of this revolution was the formulation of quantum mechanics, which could be associated with the introduction of the notion of wave function and the finding by E. Schrödinger of the equation for the wave function in 1926 [5]. The notion of density matrix generalizing the wave function to the case of thermal fluctuations was introduced in [6]; the scientific spirit of this time in Russia is shown in [7].



James Clerk Maxwell
(1831-1879)



Max Planck
(1858-1947)



Erwin Schrödinger
(1887-1961)



Lev Davidovich Landau
(1908-1968)

The Schrödinger equation and its applications to the description of vibrations of any kind, including the electromagnetic field vibrations, and the light pressure phenomenon observed by P. N. Lebedev provided a new vision of all physical processes in nature. Today, we live in the quantum era, and the behavior of elementary particles like electrons and protons, atoms and molecules, as well as the understanding of the creation and evolution of the Universe, biological processes, chemical reactions, in fact, all the natural processes one can imagine, are explained and interpreted within the framework of quantum laws.

The quantum behavior of electromagnetic vibrations, in particular, with frequencies corresponding to the visible-light electromagnetic waves, added new aspects to the light pressure observed by P. N. Lebedev. The set of theoretical and experimental researches of the phenomena, which today are called optomechanical phenomena, studied by optomechanics appeared (see, e.g., [8] and references therein). Ponderomotive

forces were studied in optomechanical phenomena by S. Mancini, V. I. Man'ko, and P. Tombesi [9].

In fact, it is a development of the Lebedev research on the interaction of the light photons with macroscopic objects. In optomechanics, the photons interact with oscillating macroscopic object (mirror), but the oscillations of the electric and magnetic fields in the electromagnetic wave and oscillations of the mirror are studied using the quantum picture of the vibrations described by the Schrödinger equation.



S. Mancini, V. I. Man'ko, and P. Tombesi



Hendrik B.G. Casimir
(1909-2000)

The classical Maxwell equations do not contain the Planck constant $h = 6.62607004 \cdot 10^{-34} \text{ m}^2 \cdot \text{kg/s}$ ($\hbar = 1.05457173 \cdot 10^{-34} \text{ m}^2 \cdot \text{kg/s}$), which is responsible for the explanation of quantum aspects of the vibrations. The formulas for the light pressure used by P. N. Lebedev and following from the classical equations for the phenomenon of light interaction with matter also do not contain the Planck constant. The formulas of optomechanics take into account the presence of the Planck constant as well as the formulas of quantum optics generalizing the formulas of classic optics. Below we discuss one of the most impressive effects of quantum nature, called the nonstationary Casimir effect, suggested at the Lebedev Physical Institute by V. V. Dodonov, O. V. Man'ko, and V. I. Man'ko [10–12], or the dynamical Casimir effect suggested by J. Schwinger [13]; see the history of the nonstationary Casimir effect in the review [14].

To understand the reason for the effect, which means the creation of photons by the action of two vibrating mirrors on the “vacuum” between the mirrors, we recall the properties of a quantum oscillator or quantum pendulum. The usual classical pendulum can be in the state of complete rest where the position and velocity of the pendulum are equal to zero. The quantum nature of the pendulum vibrations reflected by the Schrödinger equation describing all possible states of this device prohibits such states of complete rest. Such states contradict the uncertainty relation of the pendulum position and momentum discovered by Heisenberg [15] and in generalized form by Robertson [16] and Schrödinger [17].



V. V. Dodonov, O. V. Man'ko, and J. Schwinger

The Heisenberg uncertainty relation

$$(\delta x)^2(\delta p)^2 \geq \hbar^2/4,$$

where \hbar is the Planck constant and $(\delta x)^2$ and $(\delta p)^2$ are variances of the pendulum position and momentum, respectively, shows that one cannot “stop” the pendulum in its state of rest. The pendulum positions always fluctuate, and the degree of fluctuations has the bound determined by the Planck constant \hbar .

This constant is so small that, for the usual macroscopic objects and in the experiments with classical devices of the type employed by P. N. Lebedev, one cannot detect these fluctuations. Nevertheless, in modern experiments with high-precision devices the influence of quantum fluctuations of the pendulum position and momentum can be detected. We speak of a pendulum, but the quantum uncertainty relation and the Schrödinger equation, which automatically take into account the bound for the product of the momentum-and-position variances determined by the Planck constant, are valid for vibrations of any nature.

P. N. Lebedev in his experiments studied the electromagnetic field vibrations and vibrations in the waves propagating in the water; he pointed out the universality of the properties of vibrations of arbitrary kinds. His observation of the universality of vibration properties turned out to be true not only in classical physics but also in the quantum regime of vibrations unknown at the time of Lebedev's scientific activity.

The consequence of the existence of unavoidable quantum fluctuations of the electromagnetic field vibrations is the existence of the Casimir attractive force [18] between two parallel mirrors. If there is a complete vacuum (no photons) between the mirrors, the mirrors attract with a force proportional to the Planck constant \hbar . This kind of attraction is not explained by the classical Newton and Maxwell equations, which do not contain the Planck constant; this attraction is a completely quantum effect.



Werner Karl Heisenberg
(1901-1976)

If varying in time one changes the distance between the mirrors acting against the Casimir force, the work produced by such change, due to the energy conservation law, has the effect of transforming the vacuum (no photons or a state with mean photon number equal to zero) to the state with mean value of photons different from zero. This means that we have the generation of photons from the vacuum; this effect was called the nonstationary [10] or dynamical [13] Casimir effect, and it was recently observed in [2,3]. It is worth noting that photons created due to the nonstationary (dynamical) Casimir effect are in squeezed states minimizing the Schrödinger–Robertson uncertainty relations; this property of the created photons was predicted in [19].

The dynamical Casimir effect can be interpreted as the influence of negative light pressure on the mirrors, which constitute the resonator for the electromagnetic field oscillations. The attractive Casimir force of two mirrors means that the pressure in the photon “vacuum” in the resonator is opposite to the light pressure that repulses the mirrors. The joint effect of the action of external forces changing the distance between the mirrors due to the work produced by the outer sources and the Casimir forces is just the generation of light photons by the light vacuum generator. Thus, the positive light pressure measured by P. N. Lebedev in the quantum domain of the electromagnetic field vibrations in the state, where the mean number of photons between two parallel plane mirrors is equal to zero, becomes negative.

It is an interesting and unexpected quantum phenomenon that does not exist in classical physics. Also it is interesting that such light pressure in the case of another mirror geometry or another form of the resonator, e.g., spherical resonator, can be positive [20]. The other kind of vibrations is present in electric circuits constructed by the capacitance C and inductance L connected by a wire. In such electric circuits, the current and voltage vibrate exactly in a way as the position and velocity of the



Howard Percy Robertson
(1903-1961)

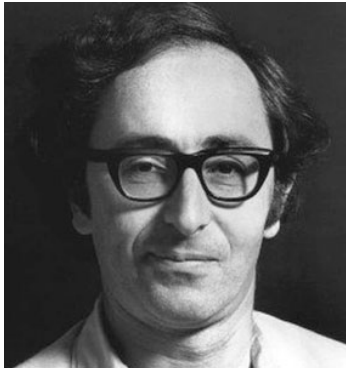
mechanical pendulum do. The frequency of these vibrations ω is determined by the circuit inductance and capacitance as $\omega \sim (LC)^{-1/2}$. If these parameters are so small that the energy quantum of the vibration $\hbar\omega$ becomes larger than the thermal energy $k_B T$, all quantum properties of the vibrations start to be visible and detectable.

First of all, quantum fluctuations of the current and voltage in the circuit (quantum noise) satisfy the Heisenberg and Schrödinger–Robertson uncertainty relations. The current–voltage characteristics of the electric circuit cannot be measured, since the current and voltage in the quantum regime of vibrations cannot be measured simultaneously with high precision. This is impossible not because there is no device in electrotechnics that can measure the current and voltage with high precision, but because such devices cannot exist, in principle, due to the quantum nature of any kind of vibrations, including the vibrations of the current and voltage in the electric circuit, which should satisfy the Heisenberg uncertainty relation.

Analogously, for a mechanical pendulum, in principle, it is impossible to measure simultaneously the pendulum position and its velocity with very high precision, since these characteristics fluctuate. The vibrations in electric circuits, if the capacitance or the inductance (or both) change in time, behave as the electromagnetic field vibrations in the resonator between two parallel mirrors forming this resonator. There was a suggestion [10–12] to employ such an electric circuit realized by the superconducting circuit, which is a device based on the properties of the Josephson junction, to generate the current in this circuit by varying the junction parameters in time.

The generation of current in a circuit with varying capacitance and inductance is completely analogous to the generation of photons in a resonator with time-varying boundaries observed in [3]. This analogy follows from the universality of quantum properties of any kind of vibrations; such properties of the nonstationary Casimir effect were recently studied in [21, 22].

The vibrations in liquids and solids provide the phenomenon of sound propagation. In the quantum picture, the sound is treated as phonons, which are analogs of photons in the case of electromagnetic-wave propagation, e.g., light propagation. In view of the universality of quantum properties of vibrations, the phonons and the sound waves should behave in specific conditions analogously to the behavior of photons and electromagnetic waves.



B. D. Josephson

For example, an analogy of the Casimir effect and nonstationary Casimir effect should exist; this means, in particular, that generation of the sound quanta (phonons) can exist in sound resonators with moving boundaries. Such possibility was discussed in sound in liquid helium, e.g., in [23]. Since the gravitational wave is the other phenomenon with vibrations of physical characteristics of the gravitational field, in view of the universality of quantum behavior of vibrations, the possibility of existence of a gravitational analog of the Casimir effect and nonstationary gravitational Casimir effect with generation of gravitons from the vacuum state can be conjectured (see, e.g., [24]). Thus, a quantum generator of gravitons or the quantum sound generator, in principle, can be thought off as possible devices of future technology.

Quantum technologies associated with the development of quantum information and quantum computing based on applications of superconducting circuits based on Josephson junctions to realize qubits are studied, for example, in [25–27].

4 Lebedev Institute

P. N. Lebedev was not only the experimentalist who measured in the laboratory the pressure of light; he also had a strong group of young colleagues and students who became famous scientists and developed further research in Russia. S. I. Vavilov was one of the representatives of the Lebedev group. During the time of Lebedev's scientific activity and later on, his laboratory was converted to the famous Physical Institute of the USSR Academy of Sciences named in 1934 *the P. N. Lebedev Physical Institute*.



S. I. Vavilov, P. A. Cherenkov, I. M. Frank, and I. E. Tamm

Academician S. I. Vavilov initiated the investigation of a charged particle moving in media with constant velocity larger than the light velocity in the media. P. A. Cherenkov, PhD student of S. I. Vavilov observed the radiation created by such moving charged particle; this radiation was called the Cherenkov radiation or Vavilov–Cherenkov radiation. A rigorous theory of the Vavilov–Cherenkov radiation was developed by I. M. Frank and I. E. Tamm, professors of the Lebedev Institute.



N. G. Basov and A. M. Prokhorov

The experimental and theoretical researches performed in the P. N. Lebedev Physical Institute by A. M. Prokhorov and N. G. Basov in the 60th years of the last century created a new area of physics and technology based on the quantum properties of photons interacting with atomic and molecular vibrations. Namely, masers and lasers were created due to the fundamental investigations of universal properties of vibrations of any kind discussed in classical physics by P. N. Lebedev but also existing in the quantum domain of the behavior of matter. It is worth mentioning that, due to a mysterious coincidence, the laboratory of the P. N. Lebedev Physical Institute where the pioneer works on the creation of masers and lasers were performed by the groups of A. M. Prokhorov and N. G. Basov was called *The Laboratory of Vibrations (Oscillations)*.

Acknowledgments

We are grateful to Prof. V. I. Man'ko for valuable comments.

References

- [1] P. N. Lebedev, *Ann. d. Phys.* (Leipzig), **6**, 433 (1901).
- [2] C. M. Wilson, G. Johansson, A. Pourkabirian, et al., *Nature*, **479**, 376 (2011).
- [3] B. P. Abbott, R. Abbott, T. D. Abbott, et al., *Phys. Rev. Lett.*, **116**, 241103 (2016).
- [4] I. Ya. Doskoch and M. A. Man'ko, *J. Russ. Laser Res.*, **36**, 503 (2015).
- [5] E. Schrödinger, *Ann. Phys.*, **79**, 361 (1926).
- [6] L. D. Landau, *Z. Phys.*, **45**, 430 (1927).
- [7] V. M. Berezanskaya (Ed.), *Conversations about Landau. A Non-stereotypical Man* [in Russian], Lenand Publisher, Moscow (2016).
- [8] D. Vitali, S. Gigan, A. Ferreira, et al., *Phys. Rev. Lett.*, **98**, 030405 (2007).
- [9] S. Mancini, V. I. Man'ko, and P. Tombesi, *Phys. Rev. A*, **55**, 3042 (1997).
- [10] V. V. Dodonov, V. I. Man'ko, and O. V. Man'ko, *J. Sov. Laser Res.*, **12**, 383 (1989).
- [11] V. I. Man'ko, *J. Sov. Laser Res.*, **31**, 563 (1991).
- [12] O. V. Man'ko, *J. Korean Phys. Soc.*, **27**, 1 (1994).
- [13] J. Schwinger, *Proc. Natl. Acad. Sci.*, **89**, 4091 (1992).
- [14] A. V. Dodonov and V. V. Dodonov, *J. Russ. Laser Res.*, **26**, 445 (2005).
- [15] W. Heisenberg, *Z. Phys.*, **43**, 172 (1927).
- [16] H. P. Robertson, *Phys. Rev.*, **34**, 163 (1929).
- [17] E. Schrödinger, *Sitzungsberichte der Preussischen Akademie der Wissenschaften, Physikalische-Mathematische Klasse*, **14**, 296 (1930).
- [18] H. B. G. Casimir, *Proc. Kon. Ned. Akad. Wetensch.*, **51**, 793 (1948).
- [19] V. V. Dodonov, A. B. Klimov, and V. I. Man'ko, *Phys. Lett. A*, **149**, 225 (1990).
- [20] T. H. Boyer, *Phys. Rev. A*, **9**, 2078 (1974).
- [21] K. Takashima, N. Hatakenaka, S. Kurihara, and A. Zeilinger, *J. Phys. A: Math. Theor.*, **41**, 164036 (2008).

- [22] T. Fujii, S. Matsuo, N. Hatakenaka, et al., *Phys. Rev. B*, **84**, 174521 (2011).
- [23] G. E. Volovik, *JETP Lett.*, **63**, 483 (1996).
- [24] M. Ruser and R. Durrer, *Phys. Rev. D*, **76**, 104014 (2007).
- [25] A. K. Fedorov, E. O. Kiktenko, O. V. Man'ko, and V. I. Man'ko, *Phys. Rev. A*, **91**, 042312 (2015).
- [26] E. O. Kiktenko, A. K. Fedorov, A. A. Strakhov, and V. I. Man'ko, *Phys. Lett. A*, **379**, 1409 (2015).
- [27] E. Glushkov, A. Glushkova, and V. I. Man'ko, *J. Russ. Laser Res.*, **36**, 448 (2015).